Simulation of the biomass dynamics of Masson pine forest under different management

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Abstract: TREE submodel affiliated with TREEDYN was used to simulate biomass dynamics of Masson pine (*Pinus massoniana*) forest under different managements (including thinning, clear cutting, combining thinning with clear cutting). The purpose was to represent biomass dynamics involved in its development, which can provide scientific arguments for management of Masson pine forest. The results showed the scenario that 10% or 20% of biomass of the previous year was thinned every five years from 15 to 40 years made total biomass of pine forest increase slowly and it took more time to reach a mature community; If clear cutting and thinning were combined, the case C (clear cutting at 20 years of forest age, thinning 50% of remaining biomass at 30 years of forest age, and thinning 50% of remaining biomass again at 40 years of forest age) was the best scenario which can accelerate speed of development of Masson pine forest and gained better economic values.

Keywords: TREE submodel; Biomass; Rate of nitrogen uptake; Dinghushan; Masson pine forest

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Introduction

Masson pine (*Pinus massoniana*) is important both economically and ecologically in subtropical mountainous areas in China, and it is vital not only as an important source of commercially harvested timber and charcoal fuel, but also as a pioneer species for restoration of vegetation in subtropical mountainous areas (Teng *et al.* 2001). Masson pine is distributed broadly through 16 provinces in China from 22º to 32° N latitude. However, due to careless management, the productivity of artificial Masson pine forest is very low. The average accumulation lumber was only 34.1$m^3 \cdot hm^{-2}$ in artificial forests, just 37.6% of average accumulation for coniferous forests in China (90.7 $m^3 \cdot hm^{-2}$) and lower than the worldwide average 110 $m^3 \cdot hm^{-2}$ (Xiao 2000). That how to manage effectively Masson pine forest has become to the focus cared by forest management, and many researches have been conducted (Wei *et al*. 2001; Qin *et al.* 1999; Ding *et al*. 1994; Ding *et al* 2002; Cheng 2002). However, these studies usually are short time and not system, and the data is absence of the long-term impact of human activity on the forest. Therefore, the simulation models for growth of a forest can be used to analyze the long-term impact of different forest management strategies by compiling the current knowledge of forest growth (Huth and Ditzer 2000) so that reasonable scenarios can be chosen in the Masson forest management practice.

The Masson pine forest in Dinghushan Biosphere Reserve, China, has been studied from difference aspects since 1980s (Peng *et al.* 1989; Huang 2000; Mo *et al.* 2002). Huang (2000) provided a simulated result on the change of soil organic matter, the content of nitrogen and productivity in succession in condition of different management measures by Century model. Mo *et al.* (1995) studied the nutrient dynamics of the human-impacted Masson pine forest. Kong and Mo (2002) investigated the population dynamics on the condition of human-impacted Masson pine forest. However, preserving much higher productivity for timber production, and accelerating the succession of Masson pine forest to stable climax communities are impending problems needing to resolve at present (Mo *et al.* 2003; Huang 2000; Ding, 2000).

TREEDYN (Bossel 1996) is originally developed to assess the future development of acacia (*Acacia auriculaeformis*) stands in South China under different conditions of silvicultural management (including thinning, cutting, litter raking, and fertilization). TREE submodel affiliated with TREEDYN model was used to simulate the biomass dynamic of Masson pine forest under different managements. The purpose of this paper was to represent biomass and nitrogen uptake dynamics by trees involved in its development, which can improve the management and sustainable development strategy of Masson pine forests in subtropical China.

Site description and data collection

This study was conducted in the Dinghushan Biosphere Reserve in southern China. The reserve is located at about 80 km west (23º08'N, 112º35'E) of Guangzhou, Guangdong Province . The area has a subtropical monsoon climate and is located in the subtropical moist forest life zone. The mean annual rainfall of 1927 mm has a distinct seasonal pattern, with 75% of it falling from March to August and only 6% from December to February

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(Huang and Fan 1982). Annual average relative humidity is 80%. Mean annual temperature is 21.0ºC, with an average temperature of the coldest (January) and hottest (July) month of 12.6℃ and 28.0℃, respectively (Mo *et al*. 1995).

The Dinghushan Biosphere Reserve occupies an area of approximately 1 200 hm^2 and contains three major forest formations: the evergreen broad-leaf forest (19% of the reserve in the core area), the mixed pine-evergreen broadleaf forests (44% of the reserve, mostly in the buffer zone), and the pine forest (12% of the reserve in the transition zone). Pine trees were planted on severely degraded land in the present transition zones (1940s) of the reserve by the local government. The land had become very damaged and eroded from clearing and overcutting of the forest for fuel because it is easily accessible to the rural population of several nearby villages. Since the later 1940s, people have been restricted from cutting trees but allowed to harvest other forms of biomass from this area. From 1956 to 1964, harvesting in the area was restricted to low levels. However, this policy was only effective for about 8 years (1956-1964) because of pressure from the local people who needed fuel (Mo *et al* 1999). The standard practice, undertaken at several times a year, is to rake the litter off the ground, cut the understory plants to the roots and rake, and sometimes trim the dead branches and twigs off the trees. So the pine forest did not turn into a mixed broadleaf-pine forest through natural succession.

Our research site was in an area of the pine forest located within the southeast corner of the transition zone of the reserve at an elevation of about 50 to 200 m above sea level. The forest canopy is generally sparse with a dense understory of shrubs, grasses, and ferns (Zhou *et al*. 1986). Age of pine tree ranged from 10 to 75 under investigation in 2000, with a mean value of 40 years at that time (Mo *et at.* 2004). In addition to pine trees in arbor layer, there were 3 eucalyptus trees. In this paper, pine forest was regarded as pure forest and the impact of three eucalyptus trees in arbor layer was ignored. The soils under the pine forest are classified as lateritic red earths, loamy in texture, acidic (pH of about 4.8), with a low base saturation (He *et al*, 1982), and shallow (generally <30 cm deep to bedrock) (Brown *et al*. 1995; Mo *et at*. 1995).

Specific leaf area（*Sla*）is a sensitive parameter in TREE submodel, and was measured in this study. Collect needles each from sun and shade sites from different height. With the canopy, a pole pruner was extended at 2 m increments vertically into the canopy beginning from the forest floor to approximately 10 m. Needle attached to small branches closest to the pole was harvested at each increment for a 200 samples. Needle samples from the field were sealed in plastic bags and placed in a cooler to retain moisture and leaf vigor. In the lab, length l and central diameter d of fresh needle were measured from 4 treatments of 200 samples (Li *et al*. 2005; White and Scott, 2006; Galmes *et al*. 2007). Leaf area S was calculated by $S = (\pi/2+l)\cdot d$. All tested needles were dried at 80ºC to a constant mass (w) and weighted to the nearest 0.1g. Specific leaf area Sla was gained from $Sla = S/W$（Zhang *et al.* 1992）(Table 1).

Table 1 Data set for Masson pine forest and site parameters for Dinghushan

Variable	Values	Source
Initial ODM of forest (tODM/ha)	1	Estimated after Mo et al., 2002
Respiration rate of leaves ($mgCO_2 \cdot dm^{-2} \cdot h^{-1}$)	1.07	Zhang et al，1989
Respiration rate of stems ($mgCO_2 \cdot dm^{-2} \cdot h^{-1}$)	0.0814	Zhang et al，1989
Respiration rate of branches ($mgCO_2 \cdot dm^{-2} \cdot h^{-1}$)	0.0543	Zhang et al，1989
Respiration rate of roots ($mgCO_2 \cdot dm^{-2} \cdot h^{-1}$)	0.0866	Zhang et al，1989
The ratio of respiration losses of stems, branches and roots to biomass (-)	0.2	Zhang et al，1989
The ratio of dark respiration losses of leaves to leaf mass (-)	0.0003	Zhang et al，1989
Light hours during vegetation period (h)	3450	Li and Wang，1984
Specific leaf area (ha/t)	0.7	This study
Withering losses of wood biomass (-)	0.06	Mo et al，2004
Summer/winter max. daylength difference (h)	4.0	Krieger et al, 1990
Mean annual temperature (℃)	21.4	Mo et al，2002
Mean annual rainfall (mm/a)	1927	Mo et al，2002

The collected data for Masson pine forest derive from published field data, and are documented in Table 1-2 (ODM – organic dried matter).

Table 2 The value of table function in TREE submodel

Variable	Values								Source
Light intensity (w/m^2)	22	80	170	217	256	326	430	1000	Liang *et al*., 1997
Photoproduction rate ($mgCO2/dm^2 \cdot h$)	0	3.5	4.4	4.8	5	5.8	5.8	5.4	
Total biomass (tODM/ha)	0	30	60	100	150	200			Estimated after Mo *et al*., 2002
Tree number (-)	4000	4000	3000	2000	600	400			
Total biom（tODM/ha）	0	32	108	186.6	197.4				Liu, 1996
Needle fraction (-)	0	0.1	0.067	0.023	0.045				
Stem fraction (-)	0	0.58	0.66	0.83	0.65				
Branch fraction (-)	0	0.2	0.16	0.042	0.17				
root fraction (-)	0	0.13	0.12	0.11	0.14				
Relative rainfall (-)	0	0.3	0.5	0.75	1				Peng, 1996
water saturation deficit (%)	50	20	10	0	0				
water saturation deficit (%)	10	20	50	100					Peng, 1996
Photosynthesis influence factor (-)	1	1	0	0					
Drought factor (-)	0	0.05	0.2	0.2					

Model description

Forest scientists in the past have very often tried to describe the temporal development of stand growth by means of data-intensive regression models, which for example, lead to the well-known growth and yield tables for common tree species of Central Europe. In addition to a dearth of data for creating such a kind of forest growth schedule for the tree species under investigation, another great disadvantage of those descriptive models is their inability to explain the reactions of tree and stand growth to altered or changing environmental conditions. Examples are the following: how will changes in mean annual temperature (climate change) affect growth? Is there an optimal thinning strategy, and what are its likely parameters? How does the nutrient balance in trees and soil develop with time, especially in the long term? TREEDYN model is a process model, and it is not a representation of empirical data, but a (crude and simplified) representation of the major processes determining tree growth, and of the mutual interaction in a complex feedback structure. These processes are parametrized by real physical or physiological parameters, which can (in principle) be determined from direct measurements in the real system. The modeling approach chosen in this paper therefore does not try to describe a given forest state as exactly as possible, but tries to represent all relevant dynamic processes involved in its development. The linking of all these processes leads to an explanatory model mapping adequately the development of a given forest at a given site as well as its reactions due to changes in environment. Moreover, the analysis and coupling of the included physiological processes included assists in detecting critical parameters crucially influencing the system's behavior (Bossel 1996; kriger *et al* 1990).

In TREE submodel, the stem, branch and root compartments and management scenarios are added, which is indicated by ellipse in the cause loop diagram of Fig. 1 that reflects the interrelations among every factor directly. In the process-oriented modeling approach, the 'average' values of Masson pine stands modeled is subdivided into different biomass fractions fulfilling different physiological functions. Each biomass fraction is represented by a state variable, the development of which is described by an ordinary differential equation. In addition to this implementation of the (more or less continuous) flows of material and information, the simulation model also contains several time-discrete parts to handle i.e. the cutting or thinning of trees, etc.

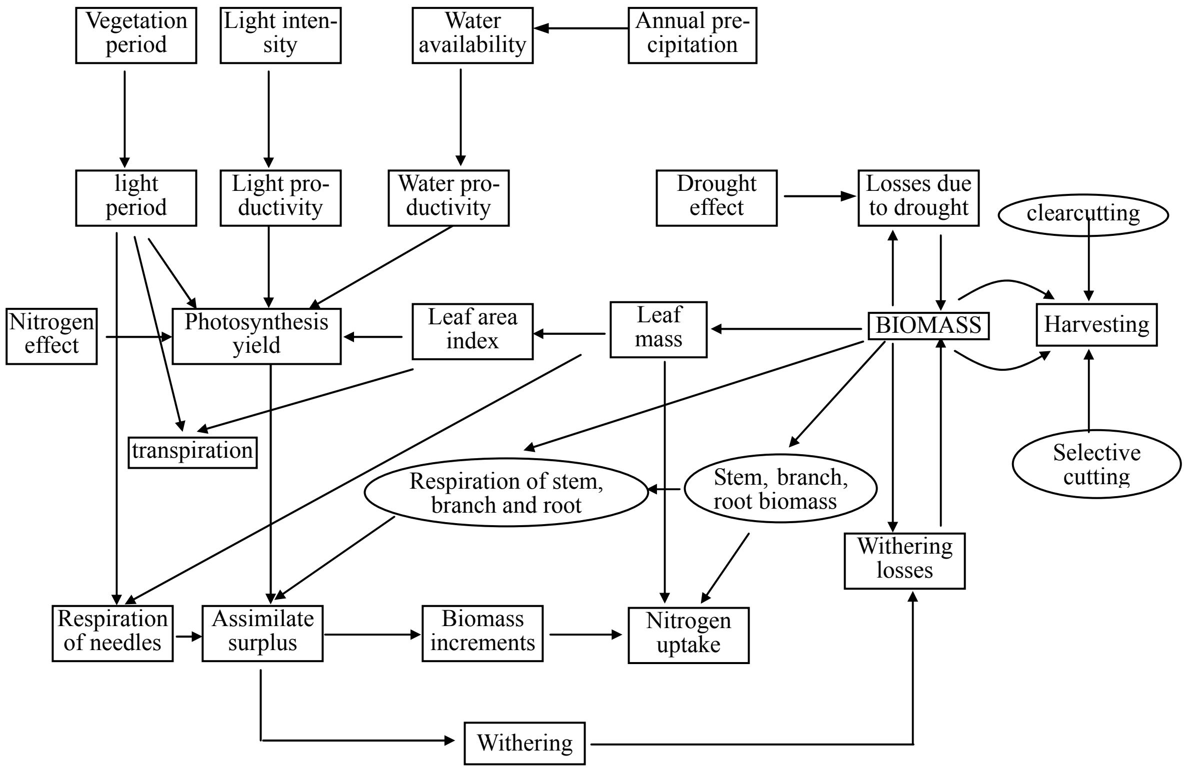

Fig. 1 Causal loop diagram of the TREE submodel (added compartments are indicated by ellipse)

Simulation results

Validation

Comparisons of model results with field data are important to evaluate model predictions. Fig. 2 shows the simulation results that the biomass increased along the typical S-type curve with superimposed annual dynamics, which is consistent with the trend simulated by other models (Lu and Deng, 1997). The biomass increases gradually to about 135tODM·hm^{-2} in the course of 50 years, and the greatest increment occurs about 20 years (Fig. 2). It is fairly close to field data (145 t·hm^{-2}) (Mo *et al*.,

2004), which illuminates the growth dynamics of Masson pine forest for selected parameters. But this biomass value is much lower than that (30a， 236 t·hm^{-2}) of the Oushuixi forest field in Fujian province at the same age(Wu *et al*. 1999). This is primarily due to human activities during the past several hundred years including agricultural production, grazing, and harvesting litter or understory. This practice occurs about 2 to 3 times a year.

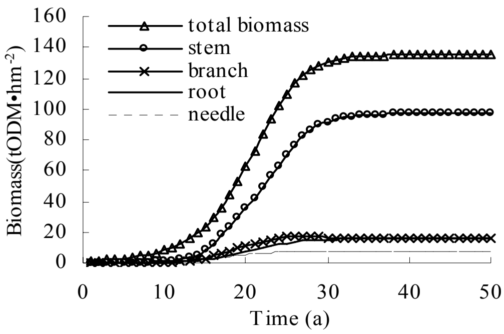

Fig. 2 Biomass simulation of Masson pine forest in Dinghushan

The value of stem volumes in successive years of Masson pine stands is derived from the average of four standard stand stems (Lu and Cheng 1996; Peng *et al*. 1989; Liu, 1996). Fig. 3 shows the simulation results of stem volumes of Masson pine forest in comparison with field that both trends of changes are identical: low at beginning and end, and high in the middle. However, there is an inverse peak occurring at 18 years, which may be caused by a high mortality rate resulting in an average decreasing of stem volumes at this time. This is not obvious in total biomass simulation (Fig. 2). Moreover, the environmental changes are complex and fluctuating so that simulation curve is smoother than test curve. At this point, it is useful to simulate the growth dynamics of Masson pine forest by the TREE submodel.

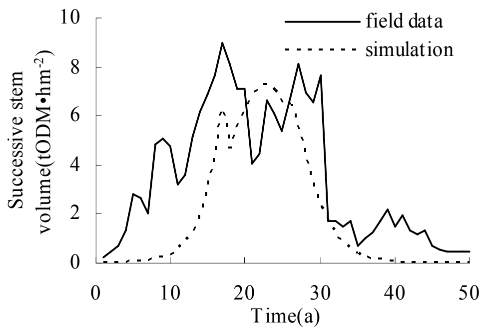

Fig. 3 Observed and simulated stem volumes in successive years of Masson pine forest

Biomass simulation

Fig. 2 represents the biomass dynamics of Masson pine forest. Stem is largest fraction in all compartments. Moreover, the biomass change of each compartment is stable after 30 years, which show that the growth of pine trees is slow due to artificial disturbances and pine forest has been close to maturity about 30 years. Artificial disturbances delayed the natural succession, and made stands always keep in the stage of pine forest.

Management simulation

Thinning

Selective and timely cutting of the afforested stands should result in a reasonable stand configuration of the forest community. This in turn ought to guarantee adequate growth of individual trees, improved productivity of the forest community and better economic returns in the form of higher lumber grades. According to the biomass dynamic of pine forest (Fig. 2), several scenarios were designed to study the influence of thinning to biomass of pine forest. Case 1 was the standard run. In case 2, 10% of the biomass of the previous year was thinned every five years from 15 to 40 years, and stoped thinning after 40 years. In case 3, the felling intensity was increased to 20% but other parameters remained constant. In case 4, 10% of the biomass of the previous year was cut every year from 15 to 40 years. Compared with the standard run (Fig. 4), total biomass in case 2 increased slowly and it took more time to reach a community climax. Total biomass in case 3 increased more slowly than that in case 2. However, both scenarios can produce the same biomass as the standard run in about 50 years. Owing to too high an intensity and frequency of thinning, the total biomass production in case 4 would be very low during the simulated rotation, which would be unprofitable. Thinning was stopped after 40 years, and the growth of forest (case 4) was the same as that in about 17 years, which affected the succession of pine forest to broadleaf forest.

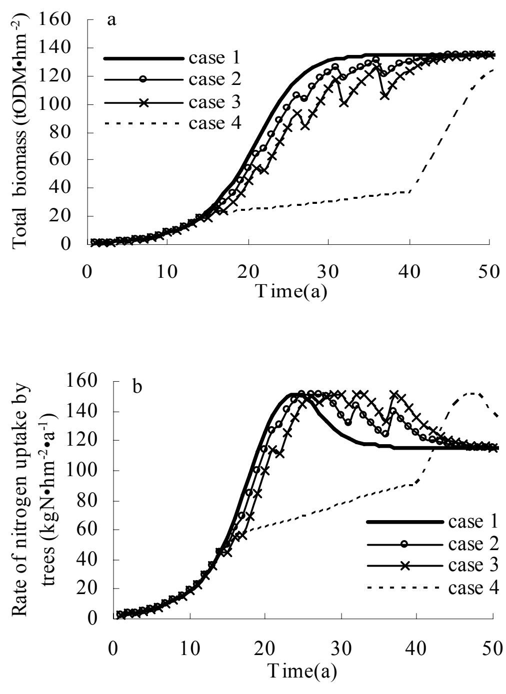

Fig. 4 The simulation of biomass and rate of nitrogen uptake by trees under different management regimes

Case 1: standard run, case 2: 10% of biomass of the previous year was thinned every five years from 15 to 40 years, case 3: 20% of biomass of the previous year was thinned every five years from 15 to 40 years, case 4: 10% of biomass of the previous year was thinned every year from 15 to 40 years

Nitrogen is one of nutritional factors supplying a need for development of plants and mineral constituents absorbed by plants

largely from the soil. The nitrogen demand for all portions of growing plants relies on their biomass and specific nitrogen content. Rate of nitrogen uptake by trees was simulated under above cases (Fig. 4b). The curvilinear trends of nitrogen absorption and biomass are identical. The rate of nitrogen uptake declines after 25 years (case 1), because the needle mass has decreased (Fig. 2) and the nitrogen content in needles is more than three times that in other components (Sha *et al.* 2002). Thinning of pine forest made the rate of nitrogen uptake by trees fluctuating from 25 to 40 years (in case 2 and case 3), which is mainly for the removal of the needle mass by harvesting. High frequency thinning (in case 4) resulted in the low rate of nitrogen uptake, which was unprofitable to the growth of trees.

Masson pine is a light tolerant species and when the canopy opens due to thinning, sunlight is able to penetrate and increases the temperature of the topsoil. This reduces the moisture content of the soil and consequently the competition of ground vegetation to the benefit of the Masson pine stands. The thinning of high frequency in scenario 4 will result in the topsoil to be exposed too long to the sun causing the surface runoff to carry off essential nutrients during heavy rainfall. This results in the formation of small old trees due to poor soil properties. The simulation results show that commercial thinning are feasible at transition periods before the stands are mature, provided we opt for specific selection regimes at appropriate times so as not to affect tree growth and the realization of economic value. Tree growth of Masson pine forest in Dinghushan is restricted by adverse site conditions such as a lack of soil thickness, fertility and from human intervention, If reasonable management measures are taken, such as thinning, and unauthorized cutting prevented, productivity of the forest community will be improved and a better utilization, in the form of industrial timber and fire wood, of Masson pine stands realized.

Clearcutting

Repeated clearcutting resulted in fluctuating of stand productivity evidently (Fig. 5a). Clearcutting the stand every ten years improved biomass production and the rate of growth. It was possible that after clearcutting other species had a great impact on pine seedlings through competition for environmental resources, as a result of fewer lateral branches and improved height and diameter growth. This should improve biomass productivity (Lan *et al.* 2003). However, clearcutting made seedling plants difficult to grow up to maturity and the physical and chemical soil properties did not improve; as a result, the cumulated biomass fluctuated and nitrogen absorption produced corresponding changes (Fig. 5b). Thus, clearcutting would cause the forest to be mature lately and this scenario does not be recommended as a single treatment.

Combining clearcutting with thinning

Provided trees were clearcut after 20 years, and when yielding 32tODM·hm^{-2} of stemwood biomass, different thinning regimes was followed. In scenario A, the reference case, all seedlings were grown for 30 years after clearcutting. In scenario B, 50% of these trees were thinned in the 30th year and in scenario C, an additional 50% of the remaining trees were cut in the 40th year after the first thinning.

The results were shown in Fig. 6a, and were also given numerically and in more detail in Table 3 (for the second period only!). Standing wood at the end of the simulation period was highest in the reference case and case B, but on account of the additional harvest of two thinnings, scenario C generated the highest total biomass (207.75 t·hm^{-2}). That thinned stand can detain over greater economic benefits than the unthinned stand (case A) the same time period. From Table 3 it appears that the cumulative photoproduction was, of course, largest in the unthinned stand, because there was no needle reduction from selective cutting. However, mainly due to a more favourable ratio of assimilation to respiration (‘heterotrophous’) tissue in the less dense stands (needle formation precedes production of wood) cumulative energy losses for maintenance and growth were smallest in case C, which, moreover, supplied the biggest bole dimensions (greater commercial value, better stability).

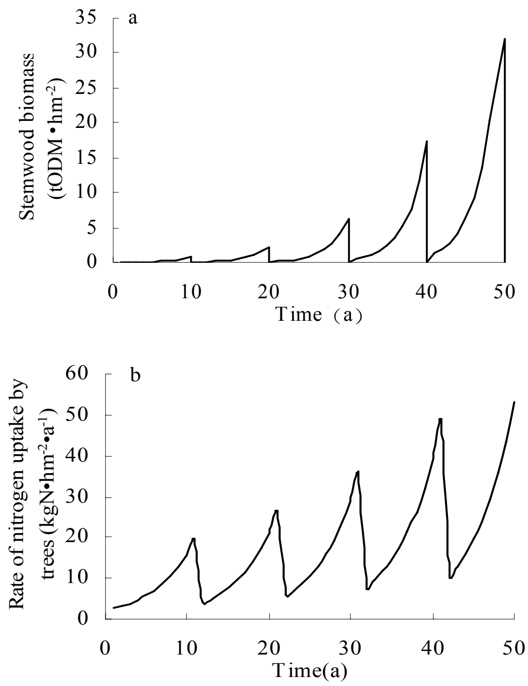

Fig. 5 The development of stemwood biomass and rate of nitrogen uptake by trees after repeated clearcutting

Table 3. Simulation results for different cutting scenarios (tODM·hm^{-2})

Scenario	A	B	C
Total biomass	135	135	130
Standing aboveground biomass	119	119	91.5
Standing stem biomass	96.9	96.7	91.1
Thinning yield	0	25.25	77.75
Cumulative photoproduction (years 20-40)	1080	1020	1010

The rate of nitrogen uptake by trees was simulated under above scenarios. The results in Fig.6b illustrated that cutting delayed the nitrogen demand of standing wood, but this demand would accelerate with increasing biomass. As well, with increasing age the stand reached maturity much later, the speed with which nourishment was returned to the soil slowed down and the trees looked after their own requirements and consume nutrients rather than returning it to the soil (Xiang and Tian 2002). Combined with heavy thinning, measures such as fertilization with carbamide if the nitrogen supply was insufficient, protection of forest vegetation and non-removal of litter can ensure the use of

available nitrogen, supplemented with that from the decomposition of vegetation. In this way, the production capacity of Masson pine forest would be enhanced and economic values realized.

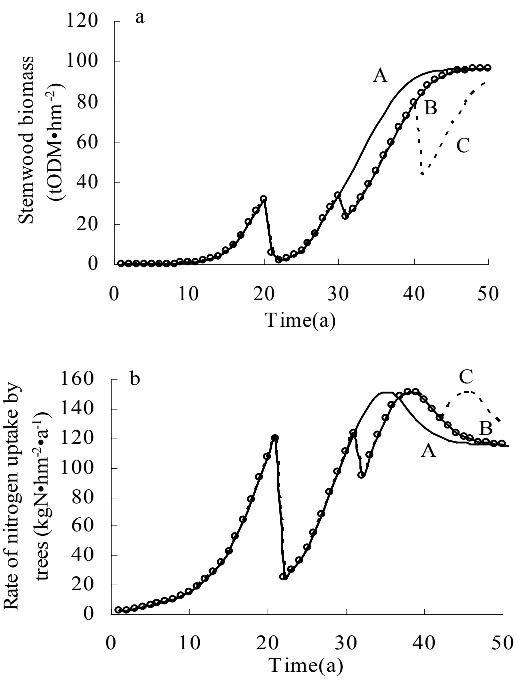

Fig. 6 The staggered development of stemwood biomass and rate of nitrogen uptake by trees under different silvicultural treatments

Conclusion and discussion

The present method of applying the results of forest research in the region has essentially been forced by scarcity. The problem has existed for decades. It is to be hoped that some changes in forest management itself will offer the opportunity to create future silvicultural measures guaranteeing a sustainable timber supply. The TREE submodel is reliable for simulating the biomass dynamics of Masson pine stands by comparing simulated values with field data. Biomass dynamics of Masson pine stands under different management scenarios have been simulated with the following results.

If 10% or 20% of the biomass was removed every five years after the trees reach 15 years of age, total biomass increased slowly and it took more time to reach a mature community. If 10% of the biomass of the previous year was cut every year from 15 to 40 years, the total biomass production would remain very low in thinned time and would be unprofitable, due to too high an intensity and frequency of thinning.

If clearcutting and thinning were combined, the biomass dynamic of pine forest in three scenarios were simulated after the clearcutting at age 20 which yielded 32 tODM·hm^{-2} of stemwood biomass. In case A, the reference scenario, the stands were reforested. In case B, 50% of the stand was removed 10 years after the clearcutting. In the third scenario, case C, the simulation model again removed 50% of the remaining trees ten years after the first thinning. The results indicated that case C was the best choice for accelerating the development of Masson pine stands and greater economic value was obtained.

The productivity of Masson pine stands in Dinghushan is very low, due to serious human disturbances (Peng *et al*. 1989). In order to be successful in community succession, we recommend in the first place that stands should be protected by renewing the physical and chemical properties of the soil, followed by reasonable thinning regimes, such as case C, which can improve productivity.

Process-based models can simulate the dynamic development of a system and show the influence of climate change and silvicultural management on future yields of forest (Bossel 1996; Shugart 1998; Kimmins 2004; Eckersten and Beierb 1998). TREE is a process-based submodel and approximately simulates the biomass dynamic trend of Masson pine forest in terms of tree physiology. The simulated results provided scientific management measures and suggested further studies for the simulation of other population dynamics. An improved version of the TREE submodel will include a calculation of soil stock flows in the relevant compartments; future applications of TREE will include the effect of mineral elements on tree growth, so that the simulation of population dynamics will represent reality more closely and be of service to forest production and management.

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